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F. Malbet, D. Buscher, G. Weigelt, P. Garcia, M. Gai, et al.. Milli-arcsecond Astrophysics with VSI, the VLTI Spectro-imager in the ELT Era. A. Moorwood. Science with the VLT in the ELT Era, Springer, pp.343-348, 2009, Astrophysics and Space Science Proceedings, 10.1007/978-1-4020-9190-2_57 . hal-00206268

HAL Id: hal-00206268
https://hal.science/hal-00206268

Submitted on 16 Jan 2008

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hal-00206268, version 1 - 16 Jan 2008

Milli-arcsecond astrophysics with VSI, the VLTI spectro-imager in the ELT era

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Summary. Nowadays, compact sources like surfaces of nearby stars, circumstellar environments of stars from early stages to the most evolved ones and surroundings of active galactic nuclei can be investigated at milli-arcsecond scales only with the VLT in its interferometric mode. We propose a spectro-imager, named VSI (VLTI

spectro-imager), which is capable to probe these sources both over spatial and spectral scales in the near-infrared domain. This instrument will provide information complementary to what is obtained at the same time with ALMA at different wavelengths and the extreme large telescopes.

At the beginning of the 21st century, infrared observations performed at the milli-arcsecond scale are essential for many astrophysical investigations either to compare the same physical phenomena at different wavelengths (like sources already observed with the VLBI or soon to be observed by ALMA) or to get finer details on observations carried out with the *Hubble Space Telescope* (HST) or 10-m class telescopes equipped with adaptive optics. The astrophysical science cases at milli-arcsecond scales which cover from planetary physics to extragalactic studies can only be studied using interferometric aperture synthesis imaging with several optical telescopes. In this respect, the *Very Large Telescope* (VLT) observatory of the *European Southern Observatory* (ESO) is a unique site world-wide with 4×8-m unit telescopes (UTs), 4×1.8-m auxiliary telescopes (ATs) and all the required infrastructure, in particular delay lines (DLs), to combine up to 6 telescopes. The *VLT Interferometer* (VLTI) infrastructure can be directly compared to the *Plateau de Bure Interferometer* (PdBI) which combines 6×15-m antenna over 500-m in the millimeter-wave domain. The quality of the foreseen images can be directly compared to the images provided by the PdBI. However, the angular resolution of the VLTI is a few hundred times higher due to the observation at shorter wavelengths. The large apertures of the VLTI telescopes and the availability of fringe tracking allow sensitivity and spectral resolution to be added to the imaging capability of the VLTI.

In April 2005, at the ESO workshop on *"The power of optical/infrared interferometry: recent scientific results and second generation VLTI instrumentation"*, two independent teams have proposed two different concepts for an imaging near-infrared instrument for the VLTI: BOBCAT [1] and VITRUV [2]. In October 2005, the science cases of these instruments were approved by the ESO *Science and Technical Committee*. In January 2006, the two projects merged in order to propose the *VLTI spectro-imager* (VSI) as a response [3] to the ESO call for phase A proposals for second generation VLTI instruments. The phase A study ended in September 2007 after an ESO board review.

1 VSI overview

The VLTI Spectro Imager will provide the ESO community with spectrally-resolved near-infrared images at angular resolutions down to 1.1 milliarcsecond and spectral resolutions up to $R = 12000$. Targets as faint as $K = 13$ will be imaged without requiring a brighter nearby reference object; fainter targets can be accessed if a suitable off-axis reference is available. This unique combination of high-dynamic-range imaging at high angular resolution and high spectral resolution for a wide range of targets enables a scientific programme which will serve a broad user community within ESO and at the same time provide the opportunity for breakthroughs in many areas at the forefront of astrophysics.

A great advantage of VSI is that it will provide these new capabilities while using technologies which have extensively been tested in the past and while requiring little in terms of new infrastructure on the VLTI. At the same time, VSI will be capable to make maximum use of the new infrastructure as it becomes available. VSI provides the VLTI with an instrument capable of combining up to 8 telescopes, enabling rapid imaging through measurement of up to 28 visibilities in hundreds of wavelength channels within a few minutes. Operations with less than 8 telescopes is the scope of the first phases of VSI. Three development phases are foreseen: VSI4 combining 4 telescopes (UTs or ATs), VSI6 combining 6 telescopes (4UTS+2ATs or 4ATs+2UTS and eventually 6ATs), and perhaps ultimately, in the long-run, VSI8 combining 8 telescopes (4UTs+4ATs or eventually 8ATs). **The current studies were focused on a 4-telescope version with an upgrade to a 6-telescope one**. The instrument contains its own fringe tracker and wavefront control in order to reduce the constraints on the VLTI infrastructure and maximize the scientific return.

2 Science cases for VSI

The high level specifications of the instrument are derived from science cases based on the capability to reconstruct for the milli-arcsecond-resolution images of a wide range of targets. These science cases are detailed below.

- **Formation of stars and planets**. The early evolution of stars and the initial conditions for planet formation are determined by the interplay between accretion and outflow processes. Due the small spatial scales where these processes take place, very little is known about the actual physical and chemical mechanisms at work. Interferometric imaging at 1 milliarcsecond spatial resolution will directly probe the regions responsible for the bulk of excess continuum emission from these objects, therefore constraining the currently highly degenerate models for the spectral energy distribution (see 1). In the emission lines a variety of processes will be probed, in particular outflow and accretion magnetospheres. The inner few AUs of planetary systems will also be studied, providing additional information on their formation and evolution processes, as well as on the physics of extrasolar planets.
- **Imaging stellar surfaces**. Optical and near-infared imaging instruments provide a powerful means to resolve stellar features of the generally patchy surfaces of stars throughout the Hertzsprung-Russell diagram. Optical/infrared interferometry has already proved its ability to derive surface

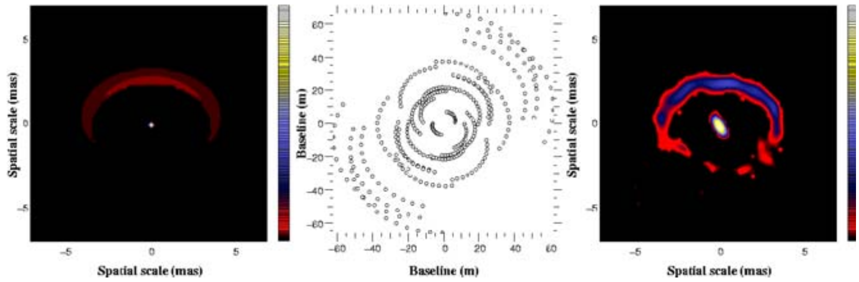

Fig. 1. Image reconstruction performed with 6 ATs on a model disk around an Herbig Ae star [4]. Left: model image; middle: coverage of the spatial frequencies; right: reconstructed image. The dust structure, the inner dust radius and the asymmetry (vertical structure) are well retrieved. Relative photometry is reliable (17% vs 19% of flux in the central star).

structure parameters such as limb darkening or other atmospheric parameters. VSI, as an imaging device, is of strong interest to study various specific features such as vertical and horizontal temperature profiles and abundance inhomogeneities, and to detect their variability as the star rotates. This will provide important keys to address stellar activity processes, mass-loss events, magneto-hydrodynamic mechanisms, pulsation and stellar evolution.

- **Evolved stars, stellar remnants & stellar winds**. HST and ground-based observations revealed that the geometry of young and evolved planetary nebulae and related objects (e.g., nebulae around symbiotic stars) show an incredible variety of elliptical, bi-polar, multi-polar, point-symmetrical, and highly collimated (including jets) structures. The proposed mechanisms explaining the observed geometries (disks, magnetohydrodynamics collimation and binarity) are within the grasp of interferometric imaging at 1 mas resolution. Extreme cases of evolved stars are stellar black holes. In microquasars, the stellar black-hole accretes mass from a donor. The interest of these systems lies in the small spatial scales and high multi-wavelength variability. Milliarcsecond imaging in the near-infrared will allow disentangling between dust and jet synchrotron emission, comparison of the observed morphology with radio maps and correlation of the morphology with the variable X-ray spectral states.
- **Active Galactic Nuclei & Supermassive Black Holes**. AGN consist of complex systems composed of different interacting parts powered by accretion onto the central supermassive black hole. The imaging capability will permit the study of the geometry and dust composition of the obscuring torus and the testing of radiative transfer models (see 2). Milliarcsecond resolution imaging will allow us to probe the collimation at the base of the jet and the energy distribution of the emitted radiation. Supermassive black hole masses in nearby (active) galaxies can be measured

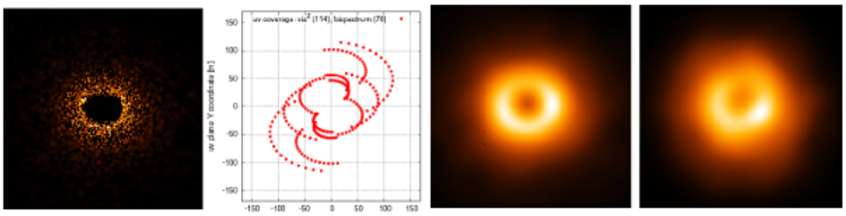

Fig. 2. VLTI/VSI image reconstruction simulation performed with 4 UTs on a model of a clumpy torus at the center of an AGN [5]. Left: model image; middle left: coverage of the spatial frequencies; middle right: model image convolved with a perfect beam corresponding to the maximum spatial resolution; right: image reconstructed from simulated VSI data using the Building Block method.

and it will be possible to detect general relativistic effects for the stellar orbits closer to the galactic center black hole. The wavelength-dependent differential-phase variation of broad emission lines will provide strong constraints on the size and geometry of the Broad Line Region (BLR). It will then be possible to establish a secure size-luminosity relation for the BLR, a fundamental ingredient to measure supermassive black hole masses at high redshift.

We have shown that this astrophysical program [4, 5] could provide the premises for a legacy program at the VLTI. For this goal, the number of telescopes to be combined should be at least 4, or better 6 to 8 at the VLTI at the time when the *James Webb Spac*e Telescope* will hammer faint infrared science ($\sim$ 2013), when HAWK-I, KMOS, will have hopefully delivered most of their science, and ALMA will be fully operational. The competitiveness and uniqueness of the VLT will remain on the high angular (AO/VLTI) and the high spectral resolution domains. In a context where the European *Extremely Large Telescope* (ELT) will start being constructed, then have first light, and, where Paranal science operations will probably be simplified with less VLT instruments and an emphasis on survey programs, VSI will take all its meaning by bringing the VLTI to a legacy mode.

3 Instrument concept

The phase A study has led to an instrument concept consisting of:

- Integrated optics multi-way beam combiners providing high-stability visibility and closure-phase measurements on multiple baselines;
- A cooled spectrograph providing resolutions between $R = 100$ and $R = 12000$ over the J, H, or K bands;
- An integrated high-sensitivity switchable H/K fringe tracker capable of real-time cophasing or coherencing of the beams from faint or resolved sources;

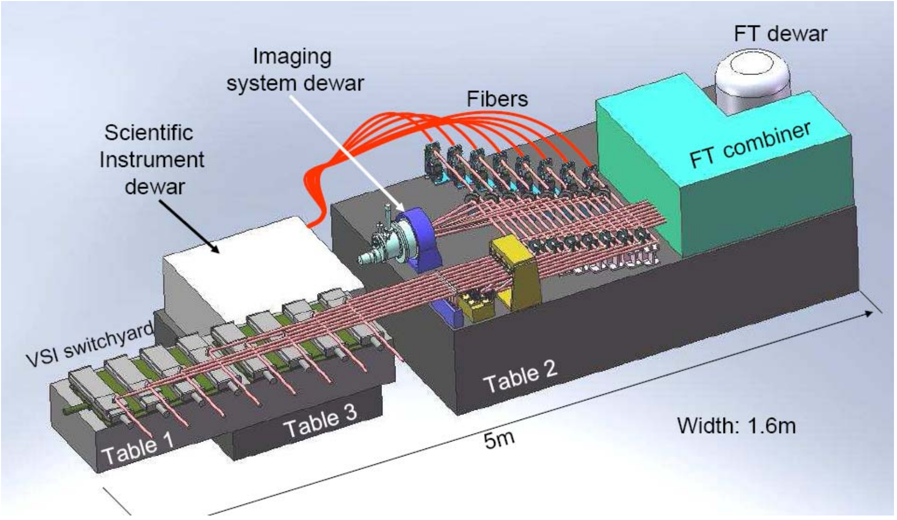

Fig. 3. General implementation of the VSI instrument

- Hardware and software to enable the instrument to be aligned, calibrated and operated with minimum staff overhead.

These features act in synergy to provide a scientific capability which is a step beyond existing instruments. Compared to the single closure phase measured by AMBER, the 3 independent closure phases available by VSI4, the 10 independent closure phases measured by VSI6 and the 21 independent closure phases measured by VSI8 will make true interferometric imaging, as opposed to simply measuring visibilities, a routine process at the VLTI. The capability to cophase on targets up to $K = 10$ will allow long integrations at high spectral resolutions for large classes of previously inaccessible targets, and the capability to do self-referenced coherencing on objects as faint as $K = 13$. It will allow imaging of >99% of targets for which no bright reference is sufficiently close by. VSI will be able to provide spectrally and spatially-resolved "image cubes" for an unprecedented number of targets at unprecedented resolutions.

A system analysis of VSI has allowed the high level specifications of the system to be defined, the external constraints to be clarified and the functional analysis to be performed. The system design [6] features 4 main assemblies: the science instrument (SI), the fringe tracker (FT), the common path (CP) and the calibration and alignment tools (CAT). The global implementation is presented in Fig. 3.

The optics design of the science instrument features beam combination using single mode fibers, an integrated optics chip and 4 spectral resolutions through a cooled spectrograph. The common path includes low-order adaptive optics (with the current knowledge reduced to only tip-tilt corrections). VSI also features an internal fringe tracker. These servo-loop systems relax the constraints on the VLTI interfaces by allowing for servo optical path length differences and optimize the fiber injection of the input beams to the required level. An internal optical switchyard allows the operator to choose the best configuration of the VLTI co-phasing scheme in order to perform phase bootstrapping for the longest baseline on over-resolved objects. Three infrared science detectors are implemented in the instrument, one for the Science Instrument, one for the fringe tracker, and one for the tip-tilt sensor. The instrument features 3 cryogenic vessels.

An important part of the instrument is the control system which includes several servo-loop controls and management of the observing software. The science software manages both data processing and image reconstruction since one of the products of VSI will be a reconstructed image like for the millimeter-wave interferometers. The instrument development includes a plan for assembly, integration and tests in Europe and in Paranal.

An instrument preliminary analysis report [7] discusses several important issues such as the comparison between the integrated optics and bulk optics solutions, the standard 4- and 6-telescope VLTI array for imaging, the proposed implementation of M12 mirrors to achieve these configurations with VSI4 and VSI6, implication of using an heterogeneous array and analysis of the thermal background.

4 Requirements on the VLTI infrastructure

The needs for future VLTI infrastructure can be summarized [8] in an increasing order of completeness as:

- Interferometry Supervisor Software (ISS) upgrade: upgrade from 4-telescope version to a 6-telescope version allows VSI to use 6 telescopes of the existing infrastructure for science cases which require imaging on a short timescale.
- AT5 and AT6: 2 additional ATs allow the VLTI to use VSI in an efficient way without fast reconfiguration of the array.

On a longer term, 8T combination at the VLTI could be foreseen but this is not a VSI priority. In any case, it would require:

- DL7 and DL8: 2 additional delay lines allow even without AT5 and AT6 to use all telescopes on the VLTI (4ATs+4UTs) and would be useful for complex imaging of rapidly changing sources.
- AT7 and AT8: could be implemented if DL7 and DL8 are procured. Then, the 8T VLTI capability could be exploited only with the ATs.

5 VSI project management

For VSI4, the management plan [9] identifies a total cost of 3986 kEuros for hardware and a manpower of 87 FTEs over 4 years before the commissioning begins. Since the instrument is designed from the beginning for maximum VLTI capacity, the VSI6 version would cost only 385 kEuros and 6 FTEs in addition to the VSI4 version. It has, however, a stronger impact on the general VLTI development, especially the ISS. Based on the letters of intent from the consortium institutes, we estimated that the consortium can provide 82 secure full time equivalents (FTEs) and possibly 33 additional FTEs. On the financial side, many institutes are already in a negotiation phase with their funding agencies. A minimum ESO contribution would be requested for procurements of ESO standard control boards and possibly for detectors and controllers of the science and the fringe tracker cameras.

Acknowledgement. The VSI phase A study has benefited from a contract by ESO, and support from JRA4 of OPTICON and from CNRS/INSU.

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